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USE OF DOPPLER RADAR IN METEOROLOGICAL OBSERVATIONS

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ABSTRACT

The U.S. Weather Bureau has been experimenting with a radar operating on the Doppler principle to determine whether apparatus of this type would detect and uniquely identify tornadoes. The principles of Doppler radar as applied to meteorology and results of recent experiments with equipment of this type are discussed. Calculations of anomalous wind speeds of 206 m.p.h. in a funnel cloud and 94 m.p.h. in a dust devil are presented in detail. In addition, data have been gathered from squall lines and isolated thunderstorms. Recommendations are made for an optimum Doppler radar system for the detection of tornadoes.

1. INTRODUCTION

A number of techniques are being employed in an effort to detect tornadoes with radar. The best known of these is identification of "hook echoes". Although this has been rather successful in a few cases, there is urgent need for a unique instrument or technique that will identify tornadoes far more frequently than has been done with the conventional type weather search radar. Following the suggestion of Brantley [4], then of Cornell Aeronautical Laboratory, the U.S. Weather Bureau began, in the fall of 1956, an experimental program to determine the feasibility of using radar operating on the Doppler principle for detection of tornadoes.

Radar employing the Doppler principle measures the instantaneous speed of any moving object relative to the observing point. In contrast, conventional weather search radar presents a plan view of the direction and range of objects from the radar station. Pulse and continuous wave systems are, in principle, capable of approximately the same range performance per average power [6]. An unmodulated continuous-wave radar yields no range information because no reference is provided on the transmitted wave that can be timed from emission to reception. It should be noted that in a system such as this, the intensity of the echo is proportional to the range weighted integral of all target cross-sections along the beam.

The Weather Bureau obtained from the U.S. Navy a 3-cm. continuous-wave Doppler radar (fig. 1), had it

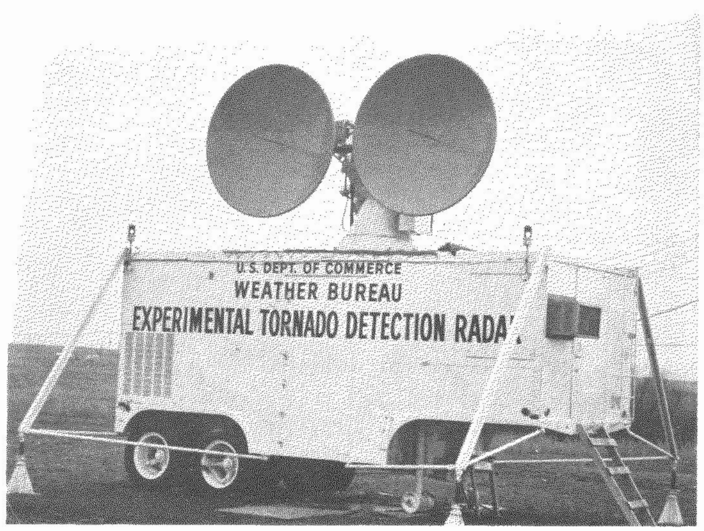

FIGURE 1.—The 3-cm. continuous-wave Doppler radar equipment trailer.

modified for meteorological use in 1957 and additionally modified in 1959. This continuous-wave (cw) radar operates on a frequency of 10,525 mc. sec.$^{-1}$. The major components of the equipment are the transmitter, receiver, and two 6-foot parabolic reflectors. The transmitter output is an unmodulated carrier which is fed into the directive transmitting antenna. The reflected signal is fed from the receiving antenna to the detector and the audio amplifier. The two parabolic reflectors, each with a beam width of 1.8°, are mounted side by side on a pedestal and rotate together. With this system, some of the transmitted energy leaks into the receiver. Thus the transmitted signal and the reflected signal are compared in the receiver. The difference between the frequencies of these two is converted to a receiver output audio tone whose pitch varies directly with the target speeds. The audio signals are recorded on magnetic tape and, at the same time, are fed into an ultrasonic frequency spectrum analyzer for immediate inspection. The tapes are used later for additional detailed analysis. The operating controls, recording and analyzing equipment are inside the body of the trailer. In addition, a radar repeater is connected to a nearby conventional weather search radar so that PPI information is readily available to the operators.

This equipment was operated during the tornado seasons of 1957, 1958, 1959 and 1960 at Wichita Falls, Tex., and Wichita, Kans. Data were gathered from isolated thunderstorms, squall lines, the El Dorado, Kans., tornado of June 10, 1958, and from a large dust devil at Wichita Falls, Tex., on March 25, 1959.

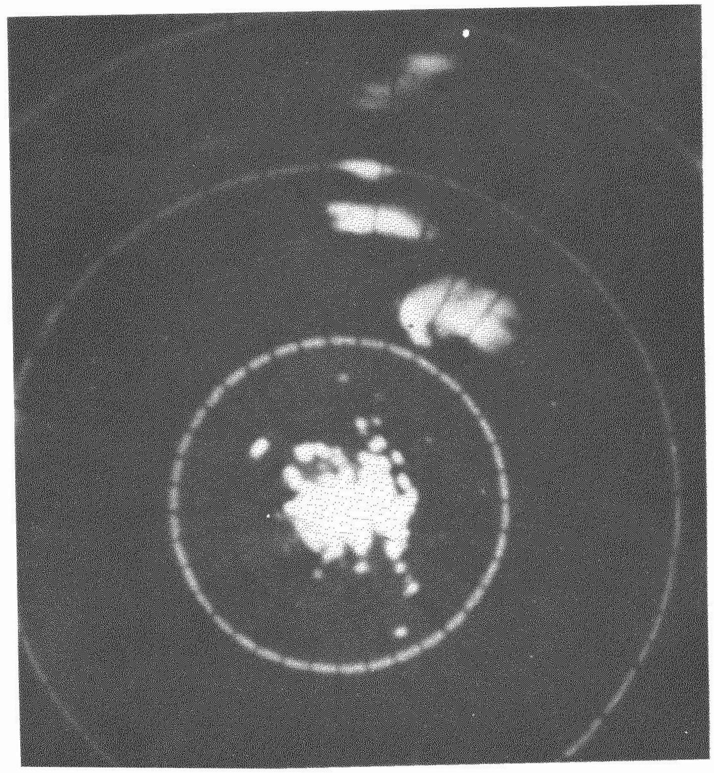

FIGURE 2.—PPI scope presentation (20-mi. range markers), 1700 CST, June 10, 1958 at Wichita, Kans., just before the time of the El Dorado tornado. Doppler radar was trained in direction of "hook".

2. DOPPLER PRINCIPLE

From elementary physics, one may recall the classic example of the Doppler effect as manifested by an approaching locomotive blowing its whistle. The trainman, being at the sound source, hears the true pitch of the whistle, while an observer down the track from the approaching train hears a higher pitch. The increase in pitch is the effect of the approaching locomotive, shortening the wavelength of the sound. From the emitted frequency f_0 the observer receives a frequency which is $f_0+\Delta f$, where Δf is the change in frequency caused by the motion of the locomotive. This small shift in frequency is called the "Doppler Effect" and is in a positive sense with an approaching sound source and in a negative sense with a departing sound source. The amount of Doppler shift is directly proportional to the speed of the sound source. The Doppler principle can also be applied to radar with the basic difference being that the speed of electromagnetic propagation rather than the speed of sound is involved. The Doppler radar equation is written:

$$\Delta f = \pm 2v f_0/c, \tag{1}$$

where Δf=Doppler frequency shift, v= radial component of target speed, f_0=transmitted frequency, and c=speed of light. Since the Doppler radar measures the magnitude of the Doppler frequency shift, this equation can be written:

$$v = |\pm \Delta f c/2f_0|. \tag{2}$$

It is emphasized that v is only the component speed parallel to the radar beam. This is often called the radial component, relative to the radar site. If the target is moving along the radar beam, v represents the true speed of the target. But if the target is moving at some angle other than that normal to the radar beam, v is some value less than the true speed of the target. If the target is moving normal to the beam, there is no Doppler effect ($\Delta f=0$); therefore $v=0$. It is important to remember that v varies directly as $|\Delta f|$.

If the horizontal limits of a given vertical section of a tornado are wholly in the radar beam, the spectrum of Doppler frequency shifts will range from zero (particles moving normal to the beam) to some maximum value (particles moving along the beam). The signal strength of these frequencies decreases slightly with increasing frequency due to normal attenuation and shear effects assuming uniform distribution of particles about the tornado vortex, with the exception of large debris which should be randomly scattered.

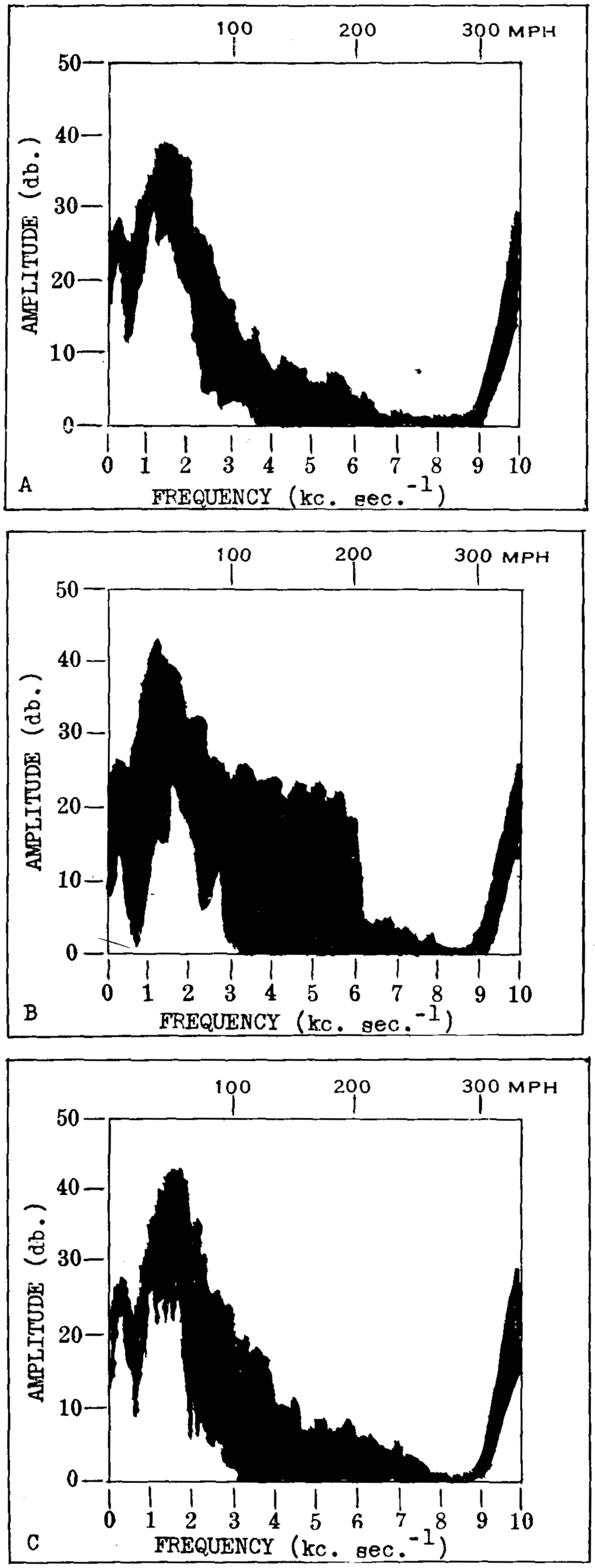

FIGURE 3.—Frequency spectrum analyses of Doppler radar signal near time of El Dorado tornado: (A) just prior to high speed signal, (B) during high speed signal, and (C) just after high speed signal.

3. DOPPLER OBSERVATIONS ASSOCIATED WITH THE EL DORADO, KANS. TORNADO OF JUNE 10, 1958

At approximately 1745 CST on June 10, 1958, a major tornado entered the city of El Dorado, Kans., killing 15 and injuring 50 persons. In addition, 150 buildings were destroyed, with total property damages amounting to an estimated $3 million.

At approximately 1715 CST signals indicating high wind speeds were received at the Doppler radar operating at Wichita, Kans. The Doppler radar beam was trained in the direction of the "hook echo" then visible on the conventional radar repeater PPI scope inside the Doppler trailer. The picture in figure 2 was taken shortly before the high speed signals were received. The "hook" is located at an azimuth of about 30° and 22 nautical miles from the radar site. It has been confirmed that the funnel cloud, which later developed into the tornado that struck El Dorado (cf. [7]), was in existence at the time the Doppler signals indicating high wind speeds were received. This funnel was observed to be well defined both in shape and in circulation. The unique returns from the funnel at the Doppler radar were limited to a very short period because of equipment malfunction that developed shortly after the observation began.

Figures 3A, 3B, and 3C are reproduced records of the frequency spectrum obtained from the ultrasonic frequency spectrum analyzer. Figures 3A and 3C represent the analyzed returns from the parent thunderstorm, excluding the funnel, and appear like those of a typical thunderstorm, while figure 3B includes analyzed returns from the funnel. This series of indications occurred when the radar beam scanned slowly in azimuth through the funnel vortex. For several seconds, the analyzer indicated signals with a plateau appearance from about 2.40 to 6.15 kc. sec.$^{-1}$ (fig. 3B). During these several seconds there were distinct audio signals of higher pitches that correspond to the high frequency returns. The plateau effect in the higher frequencies occurred at an amplitude of about 15 db. below that of the lower frequencies, indicating that the particles rotating about the funnel vortex filled but a small percentage of the echoing volume of the beam. In addition, because the funnel was not touching the ground, it is assumed that there was nearly uniform distribution of particles about the vortex.

Since the signal strength of the returned energy is directly proportional to the number of particles in the radar beam, and because there were more particles moving at low speeds than at high, it seems that these are the primary reasons for the two general levels of amplitude shown in figure 3B. Of several possibilities of the beam position during its intersection with the funnel vortex, two are shown in figure 4. Due to the continuous horizontal and slight vertical scanning, the exact beam position in the vertical, with respect to the cloud base and funnel is not certain.

Calculations using equation (2) and the highest analyzed

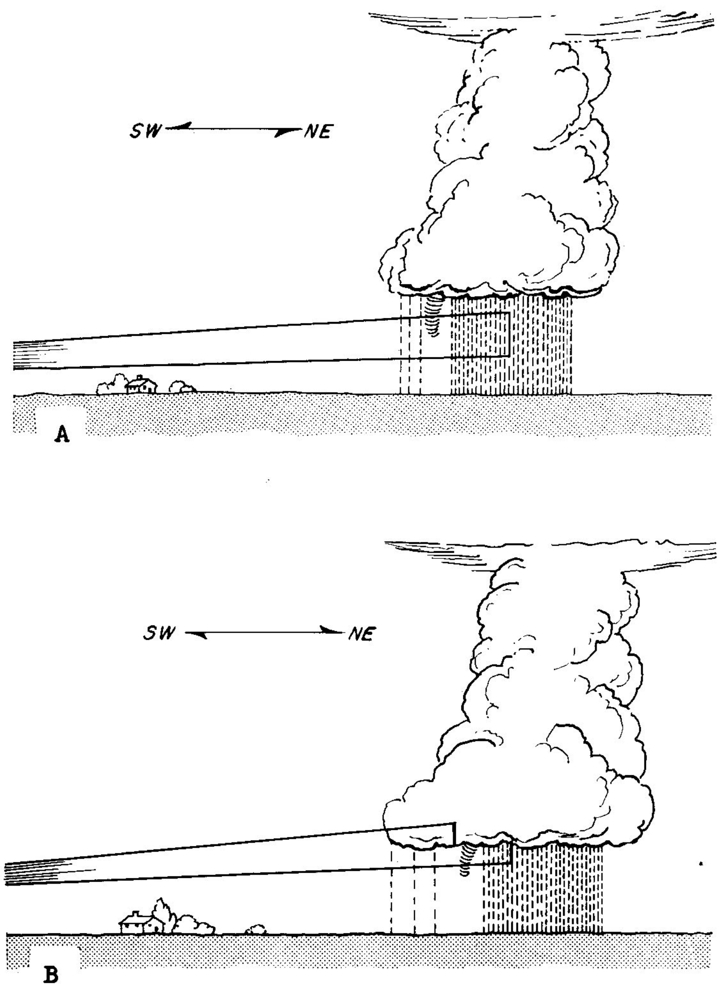

FIGURE 4.—Two possible radar beam positions at intersection with El Dorado funnel (both side views).

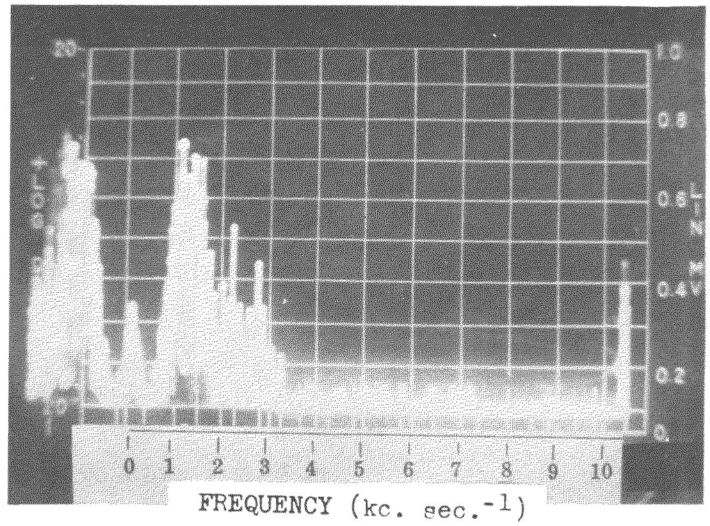

FIGURE 5.—Frequency spectrum analysis during dust devil occurrence at Wichita Falls, Tex., approximately 1410 CST, March 25, 1959.

frequency of 6.15 kc. sec.$^{-1}$ indicated a maximum speed of 206 m.p.h. Attenuation may have prevented the beam from penetrating the vortex and detecting possibly higher speeds. However, this maximum speed compares very well with speeds calculated from movies of the funnel and from the resultant structural damage in the Dallas, Tex. tornado of April 2, 1957 [2, 3, 5].

4. DOPPLER RETURNS FROM DUST DEVIL

At approximately 1410 CST on March 25, 1959, a large dust devil formed at Wichita Falls, Tex., about one-half mile from the Doppler radar site. It was about 50 yards in diameter and extended to about 300 feet above the ground. Frequencies up to 2.95 kc. sec.$^{-1}$ were indicated on the analyzer (fig. 5). Computations from the Doppler radar equation show that speeds up to 94 m.p.h. were recorded from this dust devil. Since a thunderstorm was in progress at the same azimuth and 15 miles from the radar site, signals were received from both. Those from the thunderstorm were from about 2,000 feet above the ground. The two general levels of amplitude are explained in the same way as in the case of the El Dorado tornado, with the added feature of low reflectivity of particles in the dust devil. Note that the plateau appearance exists due to the relatively uniform distribution of particles in the dust devil. The two narrow peaks of higher amplitude above the plateau might have been caused by a few large pieces of debris with greater reflectivity than the other particles in the dust devil. This case tends to support that of the El Dorado tornado in that the analyses are very similar.

5. SOME ADDITIONAL DATA GATHERED

In addition to the cases discussed above, data were gathered from many squall lines and isolated thunderstorms. Figures 6A and 6B show the PPI scope and analyzer presentations during the approach of a squall line at Wichita Falls, Tex. on April 16, 1959. The azimuth setting of the Doppler radar antennas was 290°, and the elevation angle was 0°. Indicated speeds were up to about 35 m.p.h.

Figures 7A and 7B show a case at Wichita Falls on May 9, 1959, in which high winds and hail were reported in the storm to the south. The Doppler radar antenna azimuth setting was 193° with the elevation angle ½°. Indicated speeds were up to about 65 m.p.h. near the surface in this storm. It has been observed that the region of maximum signal strength increases in frequency with increasing severity of the storm causing a shift of the spectrum to the right, due to higher velocities of a major portion of the particles.

During the 1959 season, some of the lower frequencies were excluded by use of frequency band-pass filters in the receiving system. This feature was added in order to let the higher frequencies become more audible to the operators, since the amplitude of the lower frequencies is

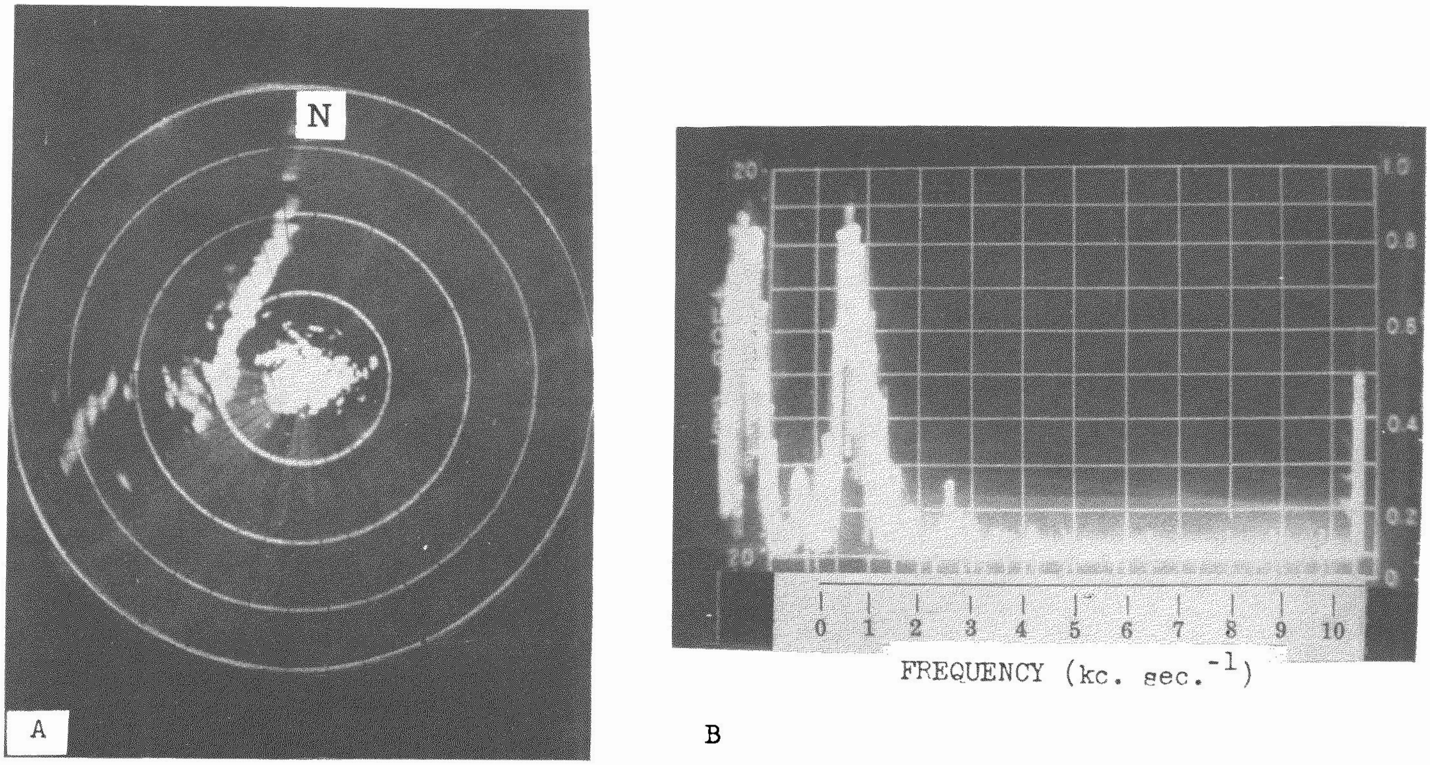

Figure 6.—(A) PPI scope (20-mi. range markers), at 2051 CST, and (B) frequency spectrum analysis at same time, during the approach of a squall line toward Wichita Falls, Tex., April 16, 1959.

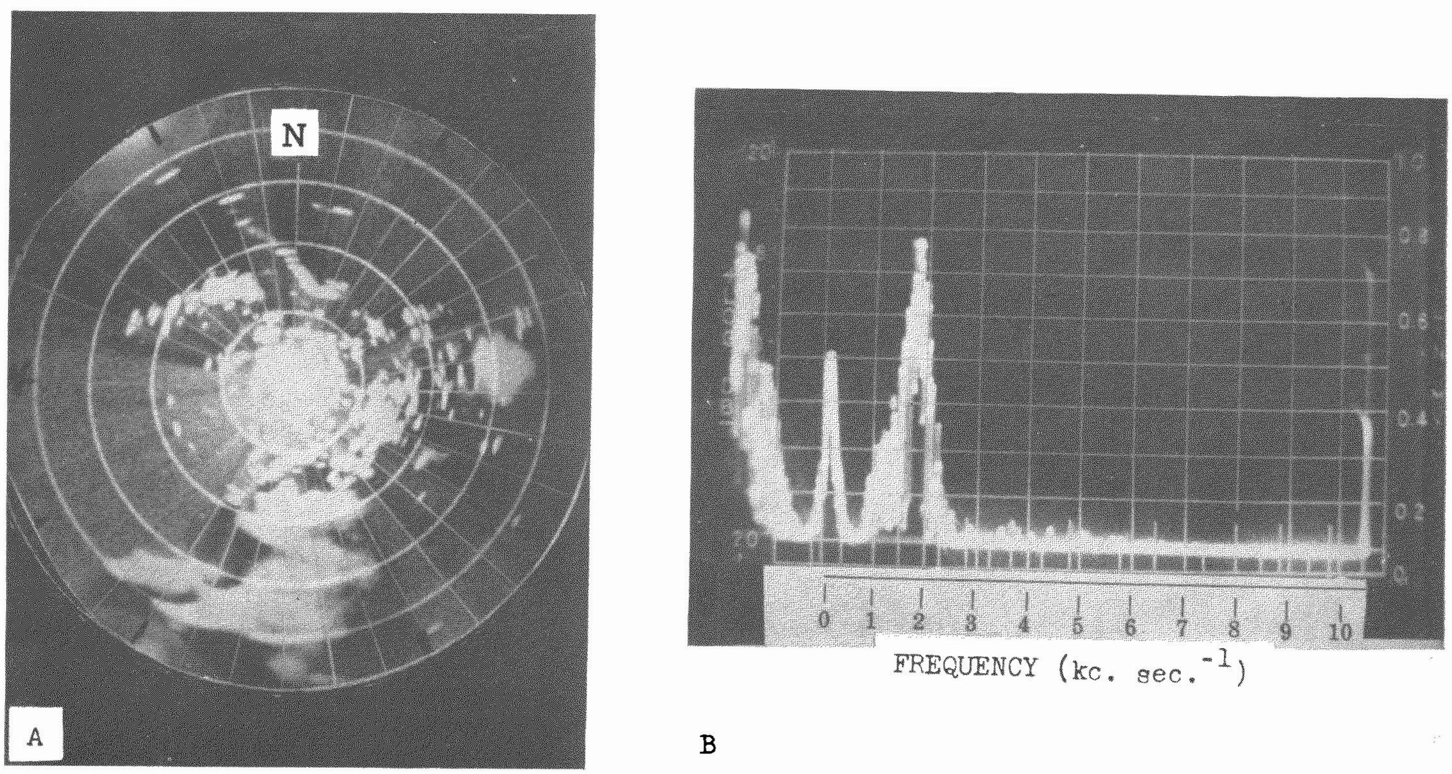

Figure 7.—(A) PPI scope (5-mi. range markers) at 2144 CST, and (B) frequency spectrum analysis, 2145 CST, May 9, 1959, at Wichita Falls, Tex. Hail and high winds were reported in the storm to the south.

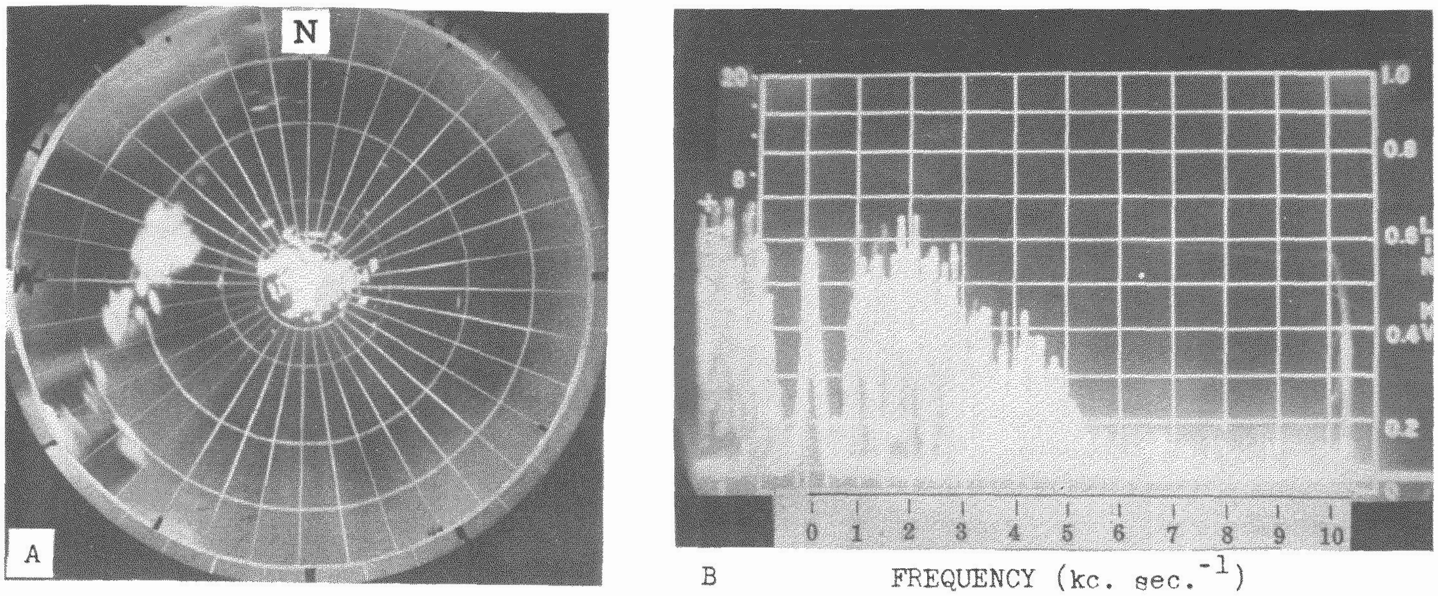

FIGURE 8.—(A) PPI scope (20-mi. range markers) at 1805 CST, and (B) frequency spectrum analysis, 1755 CST, May 19, 1959, Wichita Falls, Tex.

generally greater than that of the higher frequencies. The effect of these filters can be seen from the analyses made during the 1959 season, where the lower frequencies have been by-passed.

Figures 8A and 8B show a case where speeds were recorded from echoes about 32,000 feet above the ground in a large storm to the west of Wichita Falls on May 19, 1959. The azimuth setting of the Doppler radar antennas was 287° with an elevation angle of 10°. Indicated speeds were up to about 150 m.p.h. The significance of this figure is not understood at this time; however, it is possible that these speeds were from the anvil portion of the thunderstorm. It has been found that it is rather common to receive this type of return at these heights, but not in the lower levels, with the exception of funnel and dust devil cases. Further investigations of this phenomenon are being made.

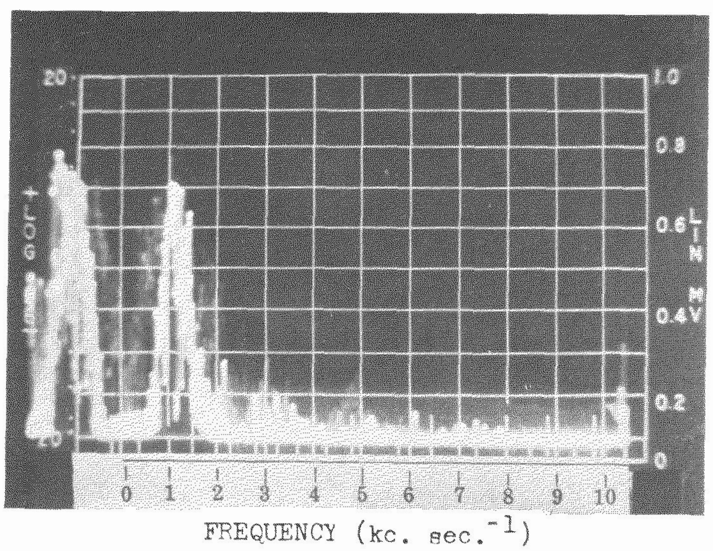

FIGURE 9.—*Frequency spectrum analysis during heavy rain at the Doppler radar site.*

Figure 9 shows the analyzer presentation when heavy rain was falling at the radar site. The elevation angle of the Doppler radar antennas was 4°, and indicated speeds were up to 45 m.p.h. It must be remembered that these speeds are the radial components, relative to the radar site, of the actual speeds of the targets. This is true in all three dimensions. This analysis represents return from rain drops only to a very short distance from the radar, due to severe attenuation. It was observed, that when light rain was occurring at the radar site, commercial aircraft of the Lockheed Constellation type could be tracked to a distance of only ¾ to 1 mile. In clear air they could be tracked to a distance of more than 30 miles. This reduction in detectable distances is, of course, due to attenuation, which is severe at this wavelength in precipitation. Therefore, when rainfall of over 0.10 inch per hour is occurring at the station the range of this radar is limited to less than 1 mile.

6. CONCLUSION

Although it appears, at this time, that Doppler radar is capable of detecting tornadoes, much additional evidence must be obtained before any firm conclusions can be reached. In addition, Doppler radar should be used for investigating cloud and clear air turbulence, velocities of falling rain, and detailed velocity patterns in hurricanes. Doppler radar might be used to determine precipitation rates in a manner similar to that used in conventional pulsed systems [1,4].

There are some major changes in the present equipment that should be made in order to have what would be considered an optimum Doppler radar for meteorological purposes. These are: (1) 5.4-cm. wavelength, (2) pulse instead of cw techniques, and (3) provision of "sense" to determine directions of motions.

The use of 5.4-cm. wavelength would reduce the attenuation problem considerably. Since there is a clear channel, 5600–5650 mc., assigned to meteorology, its use would reduce the chances of interference with other radars operating in the C-band.

The use of pulsed instead of cw techniques would allow for a tremendous increase in power output and energy penetration into storms. In addition, it would be possible to provide for range gating which cannot be done by using the cw technique. This is a very important feature, since with the reduced attenuation and increased power output, signals would often be received from two or more storms at the same azimuth from the radar site. For example, if the beam were intersecting a nearby storm at about 5,000 feet above the ground and a distant storm at about 40,000 feet above the ground, the signal return might be similar to a composite of figures 6B and 8B. This combination would appear very much like figure 3B. For this type of situation there are two possible explanations. Either a funnel or tornado exists in the nearby storm, or the high speeds are from the distant storm at high altitudes while the lower speeds are from the nearby storm. A Doppler radar system with range gating facilities would allow the operator to determine which case existed. It is worthwhile to mention, at this point, that at the time of the unique signals from the El Dorado storm, there were no other storms at the same azimuth within the range of the Doppler radar. The same is true for the storm 15 miles from the radar site, at the same azimuth as the dust devil.

Providing "sense" to the system is a feature that would show whether the Doppler shift was upward or downward in frequency, thus allowing the operator to determine if a majority of the particles were approaching or departing from the radar site. This would be especially advantageous in overhead turbulence studies in thunderstorms and in clear air.

One of the most critical problems that meteorologists have had to face has been to obtain reliable information concerning the actual existence of a tornado or funnel cloud in sufficient time to warn those in threatened areas. It is believed that Doppler radar would aid in easing this problem so that we can greatly improve our ability to prevent loss of life due to those storms.

ACKNOWLEDGMENTS

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NEW WEATHER BUREAU PUBLICATION

Climatology at Work, Measurements, Methods, and Machines, edited by Gerald L. Barger assisted by John C. Nyhan, Washington, D.C., October 1960, 109 pp. For sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. Price 65 cents.

Describes the functions, scope, and capabilities of the centralized climatological facility located at Asheville, N.C. Chapter headings are: 1. Introduction—History and Development; 2. Climatology—Selected Elements of the Science; 3. Observations—Measurement, Enumeration, and Perception; 4. Methods—Summary, Graphical, and Statistical; 5. Machines—Processing and Computing; 6. The Product—Form and Availability.

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